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Economic Feasibility of Mesquite Biomass for Electricity Production: Projections of the Long-Term Sustainability of Two Harvest Options

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Abstract Mesquite and similar woody plant species occupy over 28 million hectares in the southwestern USA and often negatively affect the rural economic sector by reducing livestock forage production, increasing bare ground, and interfering with livestock handling. Current control methods that temporarily suppress the growth of these woody plants include herbicide sprays, mechanical treatments, and prescribed fire. One alternative to current control practices is to utilize mesquite biomass for electricity generation. This study examined the economic feasibility of mesquite biomass as a potential bioenergy feedstock for electricity production using a Faustmann-type model with five mesquite biomass accumulation scenarios, which take into account variations in rates of standing biomass accumulation and tree density reestablishment after harvest with the aboveground-only (AG) harvest option or the whole-plant (WP) harvest option. The estimated regrowth functions were then incorporated into a modified version of the Faustmann model to determine the optimal harvesting length of mesquite that maximizes the net present value of a power plant using mesquite biomass. Results indicated that mesquite biomass has economic potential to be a source for electricity generation. A long-term bioenergy harvest system with regrowth following AG harvest was much more cost-effective than reestablishment from germination of new seedlings after WP harvest, even though harvest cost is higher in the AG than that in the WP harvest option. In addition, the utilization of mesquite for bioenergy would enhance other more traditional income streams from these lands including livestock grazing and wildlife hunting leases (with patterned harvesting of mesquite) and would reduce herbicide or mechanical costs that ordinarily are necessary for woody plant control. Compared to conventional coal, a lower economic return was found when the mesquite biomass was used for electricity production, but a possible carbon emission tax would make mesquite biomass competitive with conventional coal.

Keywords Bioenergy · Biomass · Carbon emission tax · Faustmann model · Mesquite · Optimal rotation length

Introduction

Mesquite (*Prosopis* spp.) and similar woody plant species occupy over 28 million hectares of grasslands and rangelands in the southwestern USA [1]. These woody plants often negatively affect the rural economic sector by reducing production of important grasses and livestock forage, increasing bare ground and soil erosion, and interfering with livestock handling [1–7]. Current control methods that either kill or temporarily suppress the growth of woody plants include herbicide sprays, mechanical treatments, and prescribed fire. However, herbicide sprays and mechanical treatments are usually very costly for land owners [4], and prescribed fire, which is the least expensive and the most convenient control option, has limited utility near rural communities because of the smoke that it generates and the potential threat of fire damage to buildings and structures in rural areas [7].

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One alternative to current control practices may be to utilize mesquite biomass for electricity generation because mesquite has characteristics that are favorable compared to other cellulosic biomass. For example, mesquite has a higher energy content (19.7 MJ kg^{-1}) than switchgrass (15.8 MJ kg^{-1}) or short-rotation woody crops, which are the main candidates for bioenergy sources among cellulosic biomass [4, 8, 9]. In addition, mesquite grows mainly on noncultivated lands (e.g., rangelands) where estimated long-term rent, \$10.83 ha^{-1} $year^{-1}$ [8], is much lower than for cropland, \$110 ha^{-1} $year^{-1}$ [9]. Mesquite also has a high regrowth potential if aboveground portions only are harvested [4], and it requires virtually no production costs (cultivation, planting, irrigation, or fertilization) [8].

Utilizing mesquite biomass in electricity production could also aid in reducing carbon dioxide (CO_2) emissions by reducing dependency on coal, which is the largest contributor to energy-related CO_2 releases into the atmosphere, where 1 kg of coal releases 3.48 kg of CO_2 into the air during combustion [9]. In addition, harvesting mesquite as bioenergy feedstock could generate additional income through increased grass production that can be used as livestock forage [10], from increasing wildlife habitat quality that could yield greater income from recreational hunting (through selective patterned harvesting of mesquite) and from savings on herbicide costs for controlling mesquite. The value-added income from increased grazing, hunting, and saved herbicide costs was estimated to be \$29.4 ha^{-1} $year^{-1}$ [11], \$12 ha^{-1} $year^{-1}$ [12], and \$16.6 ha^{-1} $year^{-1}$ [11], respectively.

However, there are some drawbacks to using mesquite as a bioenergy feedstock for electricity production. The regrowth rate of mesquite and its corresponding harvesting cost vary greatly, depending on the harvesting methods, rainfall, and soil type, and this may disrupt a stable supply of mesquite biomass for a power plant unless the harvesting option and interval of the mesquite are optimized. A previous study [4] has shown that the reestablishment of mesquite biomass from emerging seedlings following whole-plant (WP) harvest would take considerably longer than regrowth from a plant with aboveground-only (AG) harvest, although the WP harvest technique is considered to be less expensive compared to the AG harvest due to the difference in harvesting procedures. For the WP harvest, a giant blade is inserted 1–1.5 m into the ground and the taproot along with a few lateral roots and most of the AG tissue is extracted as a whole unit. In contrast, the AG harvesting option requires machinery that cuts off individual stems and loads them into a container for chipping. Consequently, the AG harvest procedure is generally more time-consuming and costly. Our personal observations of operations in the field indicate that the AG harvest could be 20–40 % higher than the WP harvest for the same size and density of trees, but published data that document this difference do not currently exist. Many of the attempts to conduct the AG harvest have used forestry equipment that is not designed to harvest lower-growing multistemmed trees, and thus, the operational efficiency is greatly compromised.

Mesquite also has a low applicability in existing power plants due to the high lignin content and fibrous structure of its woody biomass. Due to this structural limitation, mesquite biomass cannot be burned completely in the conventional firebox of existing power plants because coal mills cannot effectively produce a powder from the woody biomass [13]. Pretreatment techniques, such as torrefaction and pelletization (TOP), may be required to increase the grindability, combustibility, uniformity, density, handling ability, and energy efficiency of mesquite biomass during the electricity generation process [14, 15], but the TOP process generates a large additional production cost to power plants, which is approximately \$60 Mg^{-1} for woody biomass [16]. Given the regrowth characteristic of mesquite and the structural limitation of mesquite biomass, it will be necessary to determine a cost-effective method in order to apply mesquite biomass to electricity production and to examine whether its advantages could offset its disadvantages before it can be recommended as a potential bioenergy feedstock.

The objective of this study is to estimate the long-term economic feasibility of mesquite biomass in electricity production under five harvest scenarios which take into account variations in rates of standing biomass accumulation and tree density reestablishment after harvest using the AG or the WP harvest option. The long-term regrowth functions of mesquite under these harvest scenarios are estimated based on the mesquite regrowth data in north central Texas [4]. The estimated regrowth functions are then incorporated into a modified version of the Faustmann model [17] to determine the optimal choice of harvesting option and rotation length of mesquite that maximizes the net present value (NPV) of a power plant using mesquite biocoal, the product of biomass after the TOP process. A sensitivity analysis is also performed on selected parameter values such as the discount rate, electricity price, and harvesting and transportation costs of mesquite biomass. Following this, we examine the economic feasibility of mesquite biomass in electricity production and compare the economic return from using mesquite biomass and that from conventional coal, with the consideration of a possible carbon emission tax on coal. Finally, we discuss possible socioeconomic benefits associated with harvesting mesquite biomass and summarize our findings.

This study is unique in that the optimal forest management model (Faustmann model) is applied to mesquite biomass for bioenergy production in an economic framework. In addition, this is the first study on the economic feasibility of mesquite biomass for bioenergy production with the consideration of a possible carbon emission tax on coal, while most of the previous economic studies of bioenergy feedstocks (except corn) have focused on the most promising crops for biofuel production, such as corn stover, switchgrass, miscanthus, and sweet sorghum [9, 18–22] and there is only one study on the costs of delivered mesquite biomass based on budgeting and the simulation method [8]. This study could also suggest a sustainable and cleaner energy source to produce electricity for coal-fired power plants which are facing emerging regulations on CO_2 emission, such as the carbon pollution standard for new power plants proposed by the US Environmental Protection Agency (EPA) on March 27, 2012 [23].

Materials and Methods

Long-Term Mesquite Biomass Accumulation

The per-tree biomass accumulation from AG harvested trees and from seedlings, which could be seen as regrowth after WP harvest, was quantified to 15 and 30 years of age, respectively [4]. However, there is no data available for a long-term biomass accumulation of mesquite to estimate its long-term growth function. Therefore, we made an assumption that the per-tree biomass of 50-year-old AG and WP harvested trees would reach a maximum of 200 and 100 kg, respectively, based on our field experience (Fig. 1). The documented data, together with the assumption of the maximum biomass accumulation for 50-year-old AG and WP harvested trees, were used to estimate a logistic growth curve of mesquite in which there is an increasingly slower growth rate over time:

$$Q_i(T) = \frac{a_i}{1 + (T/b_i)^{-c_i}} \tag{1}$$

This logistic equation $Q_i(T)$, $i \in \{1, 2, 3, 4, 5\}$, represents the relationship between the tree age and total biomass of an individual mesquite tree under a harvest scenario, where T is the age of mesquite, a_i, b_i, and c_i are the coefficients to be estimated, and i is a harvest scenario associated with harvest options and tree density variations after cutting, where the default density is set to be 750 trees ha^{-1}, which is a typical mesquite density in the southwestern USA [4].

Regarding tree density variations, for a harvest scenario associated with the AG harvest (i=1), it was assumed that the original tree density of mesquite trees would be maintained because it is well documented that the AG harvest by mechanical means or the destruction of AG stems from other factors, such as fire, and causes virtually no whole-plant mortality, and all trees resprout vigorously from stem bases [10, 24, 25]. In contrast, following WP harvest, recovery of plant density must occur through the germination of new seedlings from the seed bank in the soil, or from seeding, or from transplanting young greenhouse-grown seedlings. The two latter options were considered to be impractical for remotely located mesquite stands, and the WP option thus was analyzed under natural reestablishment scenarios. The natural rate of reestablishment, even with an adequate seed bank in the soil, is a very slow process for mesquite and similar species [10, 26]. Therefore, it would be extremely unlikely that the original plant density would recover instantaneously. The rate of recovery is not well understood, but it would most likely vary with soil type and climatic conditions [26]. Thus, we developed four harvest scenarios associated with the WP harvest option (i=2, 3, 4, 5) to take into account possible tree density variations after cutting. In particular, harvest scenario i=2 is a "base case" in which tree density did not change after WP harvest. On the other hand, harvest scenarios i=3, 4, and 5 assumed that the original density of mesquite plants would recover at a steady rate (equal portions each year) within a 5-, 10-, or 20-year period.

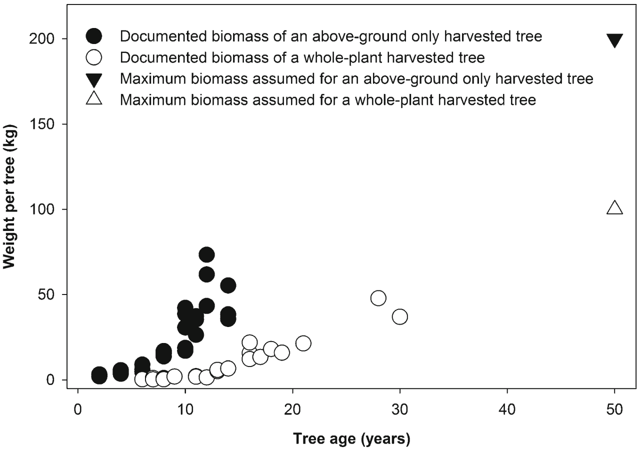

Fig. 1 Biomass accumulation per mesquite tree with respect to its age

For WP harvest scenarios i=3, 4, and 5, the projected biomass accumulation data from the estimated regrowth function of mesquite following the base WP harvest scenario (i=2) were adjusted prior to estimating the logistic regrowth function coefficients by dividing the total population of mesquite, 750 trees ha^{-1}, into an equal number of seedling cohorts over each designated time period. Thus, in the 5-year WP scenario (i=3), we assumed that density would fully recover in 5 years, with 20 % of the total population added each year. Therefore, the total plant biomass curve, $Q_i(T)$, for the 5-year WP harvest scenarios can be determined by staggering five curves of equal value by 1-year segments for the 5-year period and then computing the average of these five curves. Similarly, for the 10- and 20-year WP scenarios (i=4 and 5, respectively), we assumed that density would fully recover in 10 and 20 years, with 10 and 5 %, respectively, of the total population added each year. In all WP harvest scenarios, the assumption was made that each new seedling would grow at the same rate of biomass accumulation. Thus, for example, seedlings beginning germination in year 12 of the 20-year case have the same biomass in the first 3 years of their lives as the first 3 years of seedlings that germinated in year 1.

Faustmann-Type Optimal Rotation Model

Employing the long-term regrowth function of mesquite in Eq. (1), we can formulate the Faustmann optimal rotation model. The model was originally proposed to determine the optimal rotation length of a tree at which the maximum sustained yield can be obtained for commercial timber production, and it has been widely applied to simultaneously evaluate the economic and biological trade-offs associated with forest management when other forest values, such as water and carbon sequestration benefits, are considered in addition to timber value [27–29]. This study also modified the model by incorporating the regrowth function of mesquite in Eq. (1) and factors associated with the costs and benefits of using mesquite biocoal in electricity production to determine the optimal rotation length of mesquite that maximizes the NPV of the net income of a power plant using mesquite biocoal.

Let $\mathrm{NI}_{\mathrm{B}i}(T)$ denote the net income per hectare of a power plant using mesquite biomass per hectare when mesquite trees are harvested at the age of T years, which is the revenue from electricity sales, minus the production cost of mesquite biocoal, and minus the cost of delivered mesquite biomass under harvest scenario $i \in \{1, 2, 3, 4, 5\}$ on a per-hectare basis:

$$\mathrm{NI}_{\mathrm{B}i}(T) = \{P_{\mathrm{E}} \cdot D_{\mathrm{B}} \cdot E_{\mathrm{T}} \cdot E_{\mathrm{P}} - (C_{\mathrm{B}} + C_{\mathrm{D}} + C_{\mathrm{H}i} + C_{\mathrm{O}} + C_{\mathrm{S}})\} \cdot N \cdot Q_i(T) - C_{\mathrm{L}} \cdot T \tag{2}$$

where P_{E} is the retail price of electricity, D_{B} is the energy density of mesquite biomass, E_{T} is the energy conversion efficiency of the TOP process, E_{P} is the energy conversion efficiency of a power plant, C_{B} is the total production cost of producing mesquite biocoal excluding the cost of delivered mesquite biomass, C_{D} is the transportation cost of delivering mesquite biomass from the harvesting area to the power plant, $C_{\mathrm{H}i}$ is the harvesting cost of mesquite under harvest scenario $i \in \{1, 2, 3, 4, 5\}$, C_{O} is the operating and maintenance cost of a power plant, C_{S} is the storage cost, C_{L} is the annual lease paid to land owners, N is the density of mesquite trees per hectare, and $Q_i(T)$, $i \in \{1, 2, 3, 4, 5\}$, is the regrowth function of mesquite, which is defined in Eq. (1). The parameters in Eq. (2) are summarized in Table 1.

In Eq. (2), the cultivation cost of mesquite is omitted because the nitrogen-fixing mesquite grows naturally without fertilizers [4], and $D_{\mathrm{B}}E_{\mathrm{T}}E_{\mathrm{P}}$ represents the reduction of the energy density of harvested mesquite biomass due to the TOP process and the energy conversion process in power plants. Approximately 5 % of the initial energy density of mesquite biomass is lost in the TOP process [16], and only about 38 % of the energy density of the energy source is successfully converted to electricity in the conventional firebox of the existing power plants in the Organisation for Economic Co-operation and Development (OECD) countries [30]. This implies that 1.97 kWh of electricity can be produced from 1 kg of harvested mesquite biomass, which originally contains the energy density of 5.47 kWh [8].

Given the net income per hectare of a power plant using mesquite biomass per hectare, the NPV of a power plant over an infinite time horizon can be represented by

$$\begin{aligned}\mathrm{NPV}_i(T) &= K + \sum_{j=1}^{\infty} \mathrm{NI}_{\mathrm{B}i}(T) \cdot e^{-jrT} \\ &= K + \mathrm{NI}_{\mathrm{B}i}(T) \cdot e^{-rT} + \mathrm{NI}_{\mathrm{B}i}(T) \cdot e^{-2rT} + \ldots\end{aligned} \tag{3}$$

where r is the discount rate, j is the rotation number, and K is the net income of a power plant using mesquite biomass per hectare in the initial year (the first harvest), which would be different from $\mathrm{NI}_{\mathrm{B}i}(T)$ because the initial age distribution of mesquite would not be uniform, while $\mathrm{NI}_{\mathrm{B}i}(T)$ is the net income per hectare of a power plant from mesquite trees per hectare, which are harvested at the same age of T years. For the sake of simplicity, K is assumed to be zero when we maximize the NPV with the parameters in Table 1. Equation (3) can be rearranged as Eq. (4), and this can be further simplified into Eq. (5) by applying an infinite geometric series:

$$\mathrm{NPV}_i(T) = K - \mathrm{NI}_{\mathrm{B}i}(T) + \sum_{j=0}^{\infty} \mathrm{NI}_{\mathrm{B}i}(T) \cdot e^{-jrT} \tag{4}$$

$$\mathrm{NPV}_i(T) = K - \mathrm{NI}_{\mathrm{B}i}(T) + \frac{\mathrm{NI}_{\mathrm{B}i}(T)}{1 - e^{-rT}} \tag{5}$$

Then, the optimal rotation length T must satisfy the following condition:

$$\frac{d\mathrm{NPV}_i(T)}{dT} = -\frac{d\mathrm{NI}_{\mathrm{B}i}(T)}{dT} + \frac{[\{d\mathrm{NI}_{\mathrm{B}i}(T)/dT\} \cdot (1 - e^{-rT}) - \mathrm{NI}_{\mathrm{B}i}(T) \cdot r \cdot e^{-rT}]}{[1 - e^{-rT}]^2} = 0 \tag{6}$$

where $d\mathrm{NI}_{\mathrm{B}i}(T)/dT$ is the marginal benefit of delaying the harvest of mesquite biomass:

$$\frac{d\mathrm{NI}_{\mathrm{B}i}(T)}{dT} = \{P_{\mathrm{E}} \cdot D_{\mathrm{B}} \cdot E_{\mathrm{T}} \cdot E_{\mathrm{P}} - (C_{\mathrm{B}} + C_{\mathrm{D}} + C_{\mathrm{H}i} + C_{\mathrm{O}} + C_{\mathrm{S}})\} \cdot N \cdot \frac{dQ_i(T)}{dT} - C_{\mathrm{L}} \tag{7}$$

where $dQ_i(T)/dT$ is the marginal change in mesquite biomass accumulation with respect to the rotation length of mesquite, which can be obtained from the regrowth function of mesquite in Eq. (1).

Simplifying Eq. (6) generates the well-known Faustmann rule for optimal harvest length in the context of maximizing the NPV of a power plant using mesquite biocoal:

Table 1 Symbols used in the net income and carbon emission tax equations

Symbol	Description	Value	Reference
C_B	Total production cost of producing biocoal[a]	\$0.06 kg^{-1}	Uslu et al. [16]
C_C	Price of delivered coal	\$0.0497 kg^{-1}	EIA [33]
C_D	Transportation cost of mesquite biomass[b]	\$0.0093 kg^{-1}	Park et al. [8]
$C_{\mathrm{H}i}$	Harvesting cost for the aboveground only harvest scenario (i=1)	\$0.0445 kg^{-1}	Park et al. [8]
	Harvesting cost for the whole-plant harvest scenarios (i=2, 3, 4, 5)	\$0.0334 kg^{-1}	Assumed to be 25 % less than aboveground harvest
C_L	Lease fee paid to land owner	\$10.83 ha^{-1} year^{-1}	Park et al. [8]
C_O	Operating and maintenance cost of power plant	\$0.0075 kWh^{-1}	Katzer et al. [34]
C_S	Storage cost	\$0.0005 kg^{-1}	Park et al. [8]
D_B	Energy density of mesquite biomass	5.47 kWh kg^{-1}	Park et al. [8]
D_C	Energy density of coal	6.34 kWh kg^{-1}	EIA [35]
E_P	Conversion efficiency of power plant	0.38	WCA [30]
E_T	Conversion efficiency of TOP process	0.95	Uslu et al. [16]
E_{CO2}	$\mathrm{CO_2}$ emission from combusting 1 kg of coal	3.48 kg	Aravindhakshan et al. [9]
N	Density of mesquite trees	750 ha^{-1}	Ansley et al. [4]
P_E	Retail price of electricity	\$0.1158 kWh^{-1}	EIA [35]
r	Annual discount rate	0.05	Assumed

[a] The production cost of the torrefaction and pelletization (TOP) process for green wood, €45 Mg^{-1}, and yearly average exchange rate of Euro to dollar for 2007–2011 [36], \$1.333, are used to calculate the production cost of mesquite biocoal and the product of mesquite biomass after the TOP process

[b] The total transportation cost per kilogram load is \$0.001102+\$0.000082×round trip distance in kilometers, and we assume that the round trip distance between the harvesting area of the mesquite and the power plant is 100 km

$$\frac{[d\mathrm{NI}_{\mathrm{B}i}(T)/dT]}{\mathrm{NI}_{\mathrm{B}i}(T)} = \frac{r}{1-e^{-rT}} \tag{8}$$

This optimal condition implies that mesquite should be harvested at age T, when the marginal increase in net income from delaying the harvest of mesquite biomass for electricity production, $d\mathrm{NI}_{\mathrm{B}i}(T)/dT$, equals the sum of the marginal opportunity cost of delaying the harvest of mesquite biomass, $r\mathrm{NI}_{\mathrm{B}i}(T)$, which is a forgone interest on the net income, and of delaying the receipt of future net income, $\{d\mathrm{NI}_{\mathrm{B}i}(T)/dT\}e^{-rT}$. This can be seen by rearranging Eq. (8) as follows:

$$\frac{d\mathrm{NI}_{\mathrm{B}i}(T)}{dT} = r\cdot\mathrm{NI}_{\mathrm{B}i}(T) + \frac{d\mathrm{NI}_{\mathrm{B}i}(T)}{dT}\cdot e^{-rT} \tag{9}$$

Another interpretation of the Faustmann rule is that mesquite should be harvested at age T, when the marginal increase in net income from delaying the harvest of mesquite biomass for electricity production, $d\mathrm{NI}_{\mathrm{B}i}(T)/dT$, equals the sum of the interest that can be earned from the site value of the land, $r\{\mathrm{NPV}_i(T)-K\}$, which is what the bare ground could be sold for at time T=0, and if the net income at time T is invested at an interest rate r, $r\mathrm{NI}_{\mathrm{B}i}(T)$ [31]. This can be seen by rearranging Eq. (8) as follows:

$$\frac{d\mathrm{NI}_{\mathrm{B}i}(T)}{dT} = \left\{\frac{r\cdot(e^{rT}-1)+r}{e^{rT}-1}\right\}\cdot\mathrm{NI}_{\mathrm{B}i}(T) = r\cdot\mathrm{NI}_{\mathrm{B}i}(T) + r\cdot\{\mathrm{NPV}(T)-K\} \tag{10}$$

Let $Z_{\mathrm{E}i}(T)$ denote $D_\mathrm{B}E_\mathrm{T}E_\mathrm{P}NQ_i(T)$ in Eq. (2), which is the amount of electricity produced from mesquite biocoal under harvest scenario $i\in\{1, 2, 3, 4, 5\}$ at every rotation length of T years. Then, the net income of a power plant producing the amount of electricity $Z_{\mathrm{E}i}(T)$ using conventional coal ($\mathrm{NI}_{\mathrm{C}i}$) can be represented by

$$\mathrm{NI}_{\mathrm{C}i}(T) = P_\mathrm{E}\cdot Z_{\mathrm{E}i}(T) - (C_\mathrm{C}+C_\mathrm{O})\cdot X_i(T) \tag{11}$$

where P_E is the price of electricity, C_C is the price of delivered coal, C_O is the operating and maintenance cost of a power plant, and $X_i(T)$ is the amount of delivered coal required to produce the amount of electricity $Z_{\mathrm{E}i}(T)$. If D_C and E_P denote the energy density of coal and the energy conversion efficiency of a power plant, respectively, $D_\mathrm{C}E_\mathrm{P}$ represents the amount of energy density of coal that is successfully converted to electricity in a power plant. Therefore, the amount of coal needed to produce the amount of electricity $Z_{\mathrm{E}i}(T)$ can be calculated by

$$X_i(T) = Z_{\mathrm{E}i}(T)/(D_\mathrm{C}\cdot E_\mathrm{P}) \tag{12}$$

where the parameters used in Eqs. (11) and (12) are presented in Table 1.

For a power plant, the electricity production from mesquite biomass would be economically preferred to conventional coal if the net income from using mesquite biomass, $\mathrm{NI}_{\mathrm{B}i}(T)$, is greater than the net income from using conventional coal, $\mathrm{NI}_{\mathrm{C}i}(T)$, to produce the same amount of electricity $Z_{\mathrm{E}i}(T)$. Otherwise, mesquite biomass cannot compete with conventional coal unless certain economic incentives are provided to a power plant using mesquite biomass or unless economic penalties, such as a carbon emission tax, are imposed on the use of conventional coal in electricity generation.

Carbon Emission Tax on Net CO_2 emissions

Employing the carbon emission tax formula in the study by Aravindhakshan et al. [9], we can compute the carbon emission tax on net CO_2 emissions that would be required to make mesquite biomass equally profitable to conventional coal, $\mathrm{NI}_{\mathrm{B}i}(T)$ equals $\mathrm{NI}_{\mathrm{C}i}(T)$, in producing the same amount of electricity $Z_{\mathrm{E}i}(T)$:

$$C_{\mathrm{X}i} = \max[0, (B_{\mathrm{C}i} - C_{\mathrm{C}})/E_{\mathrm{CO2}}] \tag{13}$$

where $C_{\mathrm{X}i}$ is the carbon tax imposed on a per-kilogram basis of CO_2 emission into the atmosphere, $B_{\mathrm{C}i}$ is the break-even price of delivered coal at which harvested mesquite biomass under harvest scenario $i \in \{1, 2, 3, 4, 5\}$ is equally profitable to conventional coal, C_{C} is the current price of delivered coal, and E_{CO2} is the CO_2 emission from combusting 1 kg of coal (Table 1). The imposition of this carbon emission tax on CO_2 emission would make mesquite biomass at least an economically indifferent energy source for a power plant compared to conventional coal when the net income from utilizing mesquite biomass is lower than that from conventional coal.

Results

Long-Term Mesquite Biomass Accumulation

SigmaPlot software, with a nonlinear estimator, was used to estimate the logistic regrowth functions $Q_i(T)$, $i \in \{1, 2, 3, 4, 5\}$, in Eq. (1) for the five harvest scenarios. Table 2 presents the estimated coefficients of the regrowth functions for the five harvest scenarios, together with the statistical inferences for the AG harvest scenario ($i=1$) and the base WP harvest scenario ($i=2$). On the other hand, the statistical inferences for harvest scenarios $i=3$, 4, and 5 are not reported because the regrowth functions for these scenarios were estimated using adjusted biomass accumulation data that were originally generated from the estimated regrowth function for the base WP harvest scenario and then adjusted by the data adjustment techniques described in the previous section. The mean mesquite biomass growth curve (Fig. 2) shows that the reestablishment of biomass in trees following the AG harvest ($i=1$) is much faster than in trees following the WP harvest ($i=2$, 3, 4, 5).

Economic Returns and Optimal Rotation Length

The economic returns associated with the optimal rotation length of mesquite for the five harvest scenarios are presented in Table 3 based on the Faustmann optimality condition in equation (8). The positive NPV and the net income for all harvest scenarios suggest that mesquite biomass is an economically feasible source for electricity generation. The average net income per year, which is calculated by dividing the net income per rotation by the corresponding optimal rotation length, indicates that the AG harvest (scenario 1), with the optimal rotation length of 17 years, is the most cost-effective method for utilizing harvested mesquite biomass for electricity generation. This method would yield NPV of \$4,233 ha^{-1} and the net income per rotation of \$5,670 ha^{-1} by generating electricity of 108,175 kWh, which are approximately \$334 ha^{-1} year^{-1} and 6,363 kWh year^{-1}, respectively, if they are evenly divided by the rotation length.

The base WP harvest scenario with the optimal rotation length of 30 years generated the second-highest economic return to a power plant, but its corresponding NPV and the annual net income were only \$1,073 ha^{-1} and \$125 ha^{-1} year^{-1}, respectively, which are approximately 75 and 63 % less compared to the AG harvest scenario. These gaps in economic returns between these two scenarios suggest that the reaccumulation rate of biomass is a driving factor in determining the economics of mesquite biomass in electricity production because these scenarios assumed that there was the same density recovery of mesquite plants after the harvest and that all other factors associated with the benefits and costs of using mesquite biomass in electricity production were the same, with the exception of the harvest cost of mesquite, where it is about 25 % less in the WP than the AG harvest option. The economic returns from other WP harvest scenarios are worse than those in the base scenario because these scenarios have slower plant density reestablishment rates than the base scenario. As expected, the progressively worse the returns are, the longer it takes for the stand to fully reestablish to the original tree density. We suspect that the 5- or 10-year reestablishment scenario is probably most biologically realistic and that the base model is not biologically realistic at all as tree density would not reestablish naturally within the first year after WP harvest.

Table 4 presents the economic returns of a power plant using conventional coal that generates the same amount of electricity using mesquite biomass. The economic returns of a power plant using conventional coal are significantly higher

Table 2 Estimated regrowth function of mesquite for the five harvest scenarios

	Regrowth function of mesquite for a scenario[a] i with respect to age (T): $Q_i(T) = a_i/[1 + (T/b_i)^{-c_i}]$, where $Q_i(T)$ represents weight per tree (kg)				
Coefficients	Scenario 1 (adj R^2=0.9271)	Scenario 2 (adj R^2=0.9679)	Scenario 3	Scenario 4	Scenario 5
a_i	248.10 (48.2990)[b] (<0.0001)[c]	178.25 (49.2392) (0.0017)	170.17	162.91	158.62
b_i	25.66 (7.4111) (0.0019)	45.61 (10.1484) (0.0002)	45.88	47.00	51.45
c_i	2.12 (0.4730) (0.0001)	2.53 (0.3177) (<0.0001)	2.74	2.99	3.32

[a] Scenarios 1 and 2 denote the aboveground-only harvest scenario and the whole-plant harvest scenario, respectively, in which stand density remains unchanged from a preharvest level of 750 trees ha^{-1} , which is a typical mesquite density in the southwestern USA. Scenarios 3, 4, and 5 denote the whole-plant harvest scenarios in which stand density recovery by seedling germination requires 5, 10, and 20 years, respectively, to reach 750 trees ha^{-1}

[b] Standard error

[c] p values indicate that all estimated coefficients are statistically significant at the 0.05 level

than that using mesquite biomass for all harvest scenarios. For example, mesquite biomass could yield a maximum annual net income of \$334 ha^{-1} year^{-1} by generating electricity at 6,363 kWh year^{-1} if the AG harvest scenario was implemented, while conventional coal would yield an annual net income of \$586, which is \$252 higher than that of mesquite biomass, for generating the same amount of electricity. These differences in the annual net income between mesquite biomass and conventional coal increase as the amount of electricity generation increases because the net income per kilowatt-hour of conventional coal is \$0.0921, while that of mesquite biomass is only \$0.0524. This suggests that in a direct comparison, mesquite biomass is economically not viable to compete with conventional coal.

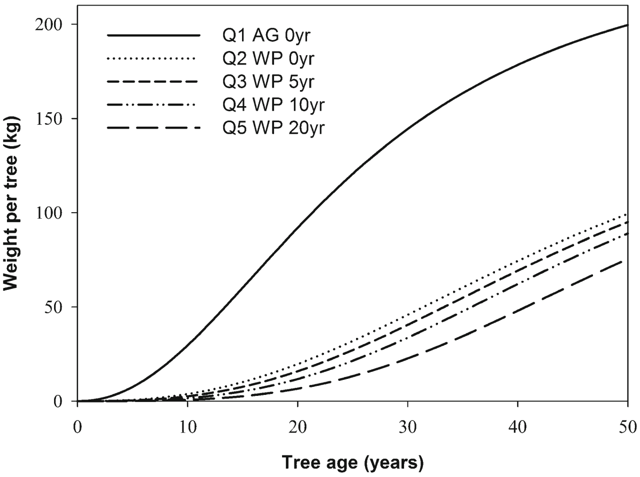

Fig. 2 Mesquite biomass accumulation curves for a mesquite tree associated with the five harvest scenarios: *Q1 AG 0 yr* and *Q2 WP 0 yr* illustrate total mesquite biomass accumulation following aboveground-only (AG) harvest and whole-plant (WP) harvest scenarios, respectively, in which stand density remains unchanged from a preharvest level of 750 trees ha^{-1}, while *Q3 WP 5 yr*, *Q4 WP 10 yr*, and *Q5 WP 20 yr* illustrate total mesquite biomass accumulation following WP harvest scenarios in which stand density recovery by seedling germination requires 5, 10, and 20 years, respectively, to reach 750 trees ha^{-1}

However, if a carbon emission tax is imposed on CO_2 emission, mesquite biomass can be an attractive alternative energy source for a power plant because the tax would increase the price of delivered coal. For example, the imposition of a carbon emission tax of \$27.44 per Mg of CO_2 emission results in a significant increase in the price of delivered coal, up to \$145.20 per Mg from \$49.7 per Mg, resulting in generating a net income per kilowatt-hour of \$0.0524 for a power plant, which is identical to that of utilizing mesquite biomass in electricity production under the AG harvest scenario. Similarly, a carbon emission tax of \$25.67 to \$26.45 is required in order for utilizing mesquite biomass following the WP harvest scenarios to be an economically viable alternative to conventional coal. Table 4 presents the amount of carbon emission tax on CO_2 emission that would make mesquite biomass at least an economically indifferent energy source to conventional coal for a power plant under the five harvest scenarios. These estimated carbon emission taxes in Table 4 are similar to the estimated EU allowance price in the third phase (2013–2020) of EU emissions trading systems, which is €22 Mg^{-1} [32]. Although there could be many differences between the EU and USA, the prediction of an average of €22 Mg^{-1} of the EU allowance price suggests that the estimated carbon emission taxes in Table 4 could be possible in the USA and would make mesquite biomass an economically feasible alternative to conventional coal.

Sensitivity Analysis

Sensitivity analyses (Table 5) were conducted to evaluate the impacts of key parameters in Eqs. (2) and (3), such as discount rate, price of electricity, and harvesting and transportation costs of mesquite biomass, on the optimal rotation length of mesquite and its corresponding economic returns to a power plant using mesquite biomass. Sensitivity analysis indicates that the optimal rotation length of mesquite and the economic return of a power plant are mainly sensitive to changes in the discount rate and the price of electricity. On the other hand,

Table 3 Economic returns, biomass, and electricity productions associated with the five harvest scenarios

Productions and economic returns	Unit	Harvest scenarios[a]				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Average biomass yield per year[b]	kg ha^{-1} year^{-1}	3,222	1,147	1,115	1,054	929
Average electricity yield per year[b]	kWh year^{-1}	6,363	2,266	2,201	2,081	1,834
Average net income per year[b]	\$ ha^{-1} year^{-1}	334	125	121	114	99
Biomass yield per rotation	kg ha^{-1} rotation^{-1}	54,782	34,423	36,789	37,938	38,075
Electricity yield per rotation	kWh rotation^{-1}	108,175	67,975	72,646	74,916	75,185
Net present value	\$ ha^{-1}	4,233	1,073	947	809	598
Net income per rotation	\$ ha^{-1} rotation^{-1}	5,670	3,737	3,983	4,087	4,048
Net income per kWh	\$ kWh^{-1}	0.0524	0.0550	0.0548	0.0545	0.0538
Rotation length	Year	17	30	33	36	41

[a] Scenarios 1 and 2 denote the aboveground-only harvest scenario and the whole-plant harvest scenario, respectively, in which stand density remains unchanged from a preharvest level of 750 trees ha^{-1}, which is a typical mesquite density in the southwestern USA. Scenarios 3, 4, and 5 denote the whole-plant harvest scenarios in which stand density recovery by seedling germination requires 5, 10, and 20 years to reach 750 trees ha^{-1}, respectively

[b] The average biomass yield per year, average electricity yield per year, and average net income per year are obtained by dividing biomass yield per rotation, electricity yield per rotation, and net income per rotation by the corresponding optimal rotation length, respectively

changes in harvesting and transportation costs only affect economic returns of a power plant.

Discussion

This study examined the economic feasibility of the invasive semiarid shrub/tree species mesquite as a bioenergy feedstock source for electricity generation by identifying the NPV of a power plant utilizing mesquite biomass to produce electricity. Positive economic returns for all harvest scenarios suggest that mesquite biomass is economically feasible for electricity production. In particular, the AG harvest, with 17 years of rotation length before reharvest of basal coppice, generated the largest economic returns to a power plant. The AG harvest option was more economically viable than the WP harvest plan because the growth rates following the AG harvest were much greater than growth rates from newly developing seedlings. In addition, the AG harvest option was more viable because tree density would never decline—essentially all AG harvested trees would coppice immediately after harvest—whereas, in the WP option, the tree density level would have to reestablish. The combined effect of slower growth from seedlings as opposed to coppice and natural reestablishment of stand density made the WP harvest option much less attractive under scenarios of stand density naturally reestablishing from seeds in the soil seed bank within 5, 10, or 20 years. Our experience and observations indicate that the 10-year period is probably the more likely time interval for full recovery of stand density from the germination of new seedlings, although this would vary depending on site, growing season length, soil type, and moisture availability.

Regarding the economically optimum 17-year rotation for reharvest of coppice in the AG scenario, we regard this as too

Table 4 Economic returns, biomass, and electricity productions associated with the five harvest scenarios

Economic factors	Unit	Amount of electricity produced from mesquite biomass with the five harvest scenarios[a]				
		6,363 kWh year^{-1} (scenario 1)	2,266 kWh year^{-1} (scenario 2)	2,201 kWh year^{-1} (scenario 3)	2,081 kWh year^{-1} (scenario 4)	1,834 kWh year^{-1} (scenario 5)
Average net income per year	\$ year^{-1}	586	209	203	192	169
Break-even price of coal	\$ Mg^{-1}	145.20	139.04	139.38	140.07	141.76
Carbon tax on net CO_2 emissions	\$ Mg^{-1}	27.44	25.67	25.77	25.97	26.45
Difference in the net income per year[b]	\$ year^{-1}	252	84	82	78	70
Net income of power plant	\$	9,958	6,258	6,688	6,897	6,921

[a] Scenarios 1 and 2 denote the aboveground-only harvest scenario and the whole-plant harvest scenario, respectively, in which stand density remains unchanged from a preharvest level of 750 trees ha^{-1}, which is a typical mesquite density in the southwestern USA. Scenarios 3, 4, and 5 denote the whole-plant harvest scenarios in which stand density recovery by seedling germination requires 5, 10, and 20 years, respectively, to reach 750 trees ha^{-1}

[b] Difference in the net income per year=Annual net income of a power plant using coal−Annual net income of a power plant using mesquite biomass

Table 5 Sensitivity analysis for interest rate, price of electricity, and harvesting and transportation costs of mesquite biomass

Productions and economic factors	Unit	Base[a]	Discount rate		Price of electricity ($ kWh^{-1})		Harvesting cost ($ ha^{-1})		Transportation cost[b] ($ kg^{-1})	
			+25 % (0.0625)	−25 % (0.0375)	+25 % (0.1448)	−25 % (0.0869)	+25 % (0.0556)	−25 % (0.0334)	+25 % (0.0114)	−25 % (0.0073)
Biomass yield per rotation	kg ha^{-1} rotation^{-1}	54,782	49,941	64,328	54,782	59,586	54,782	54,782	54,782	54,782
Break-even amount of coal	kg	44,901	40,934	52,726	44,901	48,839	44,901	44,901	44,901	44,901
Break-even price of coal	$ Mg^{-1}	145	145	145	145	145	159	132	148	143
Carbon tax on net CO_2 emissions	$ Mg^{-1}	27.44	27.48	27.39	27.44	27.41	31.34	23.54	28.18	26.74
Electricity production per rotation	kWh rotation^{-1}	108,175	98,618	127,027	108,175	117,663	108,175	108,175	108,175	108,175
Net present value	$ ha^{-1}	4,233	3,005	6,418	6,570	1,895	3,778	4,688	4,147	4,314
Net income per rotation	$ ha^{-1}	5,670	5,164	6,669	8,802	2,766	5,061	6,280	5,555	5,780
Net income per kWh (mesquite)	$ kWh^{-1}	0.0524	0.0524	0.0525	0.0814	0.0235	0.0468	0.0581	0.0514	0.0534
Net income per kWh (coal)	$ kWh^{-1}	0.0921	0.0921	0.0921	0.1210	0.0631	0.0921	0.0921	0.0921	0.0921
Optimal rotation length	Year	17	16	19	17	18	17	17	17	17

[a] The aboveground-only harvest scenario is used for the base case

[b] The upper and lower transportation costs of biomass are calculated based on the round trip distances of 75 and 125 km, respectively, which are a 25 % decrease and increase from the base distance of 100 km

long of a period to be satisfactory to ranchers who are interested in multiple uses of the pastures that include livestock grazing. Typically, grass growth that is used for grazing will flourish for 7–8 years after mesquite is harvested, but at about 10 years, mesquite regrowth begins to outcompete grasses for water and light. Thus, from a livestock production standpoint—and a selling point for ranchers to commit their pastures to periodic mesquite harvest in the AG scenario—harvesting every 10–12 years would be more attractive. Therefore, a biomass operation based on the AG scenario may have to settle for a less than optimum harvest cycle in order to acquire enough land area through rancher agreements to supply the conversion plant.

Mesquite biomass as a "stand-alone" primary feedstock cannot compete with conventional coal unless economic penalties, such as a carbon emission tax, are imposed on the use of conventional coal for electricity generation. However, there are additional ecological and agricultural benefits associated with harvesting mesquite for bioenergy purposes that add to the potential viability of this species as an alternative to conventional coal. Because this species has invaded what were once primarily grasslands and competes heavily with grasses, the periodic harvest of aboveground portions of this species, or the harvesting of the whole plant (as in the WP option), would increase grass production and grass species diversity [24]. Mesquite reduction through harvest would also lower soil erosion potential due to the increased grass cover [3, 24] and potentially increase off-site water yields into rivers and streams due to woody plant control [11]. In addition to providing ecosystem stability, the increased grass production would lead directly to increased agricultural income through grazing of grass-feeding livestock such as cattle. Moreover, leave patches and strips of unharvested mesquite among harvested areas would increase wildlife habitat diversity in a planned harvest scheme.

The increased diversity of landscape physiognomies that would benefit wildlife would also occur if different portions of a region were harvested in different years in a harvest rotational scheme, as illustrated by Park et al. [8]. In Park's study, the rotation was based on a 10-year cycle, and the current paper indicates that a more economically viable rotation would be between 16 and 19 years for the AG harvest option (Table 5); thus, under the most optimum rotation, physiognomic diversity of mesquite growth forms would be enhanced even further. The improved wildlife habitat would lead to increased wildlife populations, and this could increase income from wildlife hunting leases, which are a very large source of income in the regions of the USA where species like mesquite grow. Further research is needed to evaluate these factors by developing a spatially integrated socioeconomic framework for the development of the rural-based bioenergy industry.

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